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Recent researches by Withrow and Boyd (reference 1) and by Schnauffer (reference 2), each using a different technique, have shown that the phenomenon of knocking is accompanied by an apparently simultaneous reaction of the last part of the charge to burn. Whether the reaction of this part of the charge is actually simultaneous or whether the reaction zone travels with a very high velocity, has not yet been determined. In any case, it will be conceded that the progress of the reaction zone is too rapid to be dependent upon the transfer of heat energy by conduction from the flame front as in normal combustion. In the light of these researches and others, some of which have been carried on in the Aeronautical Engine Laboratory of the Massachusetts Institute of Technology, I believe it is possible to postulate a very simple and reasonable theory of knocking, which fulfills all present requirements and which may in some degree help to remove the veil of mystery which has surrounded the subject.

Ricardo's theory that knocking is auto-ignition in the last part of the charge to burn, was discarded because of the failure of the theory to explain why fuels do not knock in order of their ignition temperatures. This simple theory has recently been reaffirmed by the work referred to above, though there has been no explanation of the apparent contradiction. A simple extension of the theory, which will be presented, shows that no real contradiction exists.

Experiments conducted in this laboratory have shown that detonation in an engine becomes more severe as the speed is reduced, even though the volumetric efficiency is kept constant, and the spark advance is set for the best power (with nondetonating fuel) in each case. Marvin and Best (reference 3) have shown that under these conditions the rate of flame travel is nearly proportional to the r.p.m., and the only considerable change in the cycle is in the time of burning. It is well known that an engine equipped with two diametrically opposite spark plugs will detonate more when one plug is not operating, even though the maximum pressure and temperature are lower. The effect of turbulence in accelerating the flame travel and suppressing detonation is also common knowledge. These facts lead to the inescapable conclusion that, in the detonation process, <u>there must be a time effect</u>. The very beautiful experiments of Tizard and Pye (reference 4) on the auto-ignition temperature of fuels heated by compression give us a valuable clue. Tizard and Pye showed that after a certain condition of temperature and pressure is reached in their machine there is a considerable time lag before ignition takes place. They show that this lag exists, even though gaseous fuels are used. The pressure records from Tizard and Pye's experiments show that during this time lag there is a falling pressure in the chamber, indicating a certain amount of cooling due to the cylinder walls. The fact that the mixture fires after this cooling has taken place, they attribute to the presence of a temperature gradient from the center of the chamber to the wall, and the statement has been made that the temperature of the center portion of the charge must progressively increase before ignition takes place. This seems an unnecessary and perhaps illogical conclusion. The presence of a time lag may equally well indicate that ignition will not take place unless the temperature is raised to a certain point and kept there for a definite length of time. Ignition would probably take place at a lower temperature if cooling were not a factor. The experiments of Tizard and Pye show that the time lag decreases with increasing temperature of compression which, of course, is exactly what might be expected. Time lags as long as 3/4 of a second were recorded. This may be compared with the time of combustion at 1,000 r.p.m., normally less than 0.01 second, a large part of which is in the early stages when the temperature and pressure are low. While some of the results of Tizard and Pye were later shown to be inaccurate, qualitatively the work is still valid.

The mechanism of the time lag need not concern us here. It is a question for the physical chemist rather than for the engineer. Suffice it to say that there appears to be good evidence that such a lag exists. Assuming a compression exponent of $n = 1.3$ (this being approximately correct for the conditions of compression (reference 5)), a simple calculation making due allowance for the products of a combustion of the previous cycle for a compression ratio of 3.75 will reveal the rather astonishing fact that the self-ignition temperature of normal heptane may easily be reached at the temperature of compression. ("Self-ignition temperature" is used throughout to designate the temperatures as determined by Fenning and Cotton.) (Reference 6.) It is known, however, that normal heptane can be used in an engine with this compression ratio without causing knock. Granting the presence of even a very short time lag, the explanation of this fact is very simple. Although the temperature of the last part of the charge to burn is raised to the point of self-ignition at the end of the compression stroke and considerably above this point before it finally is consumed, it does not have sufficient time to complete the necessary physical or chemical preliminaries to self-ignition before the flame front passes through it and it is completely burned. We now have a complete picture of what happens to this "last part of the charge to burn." It is first compressed by the action of the piston, and then by the combined action of the piston and the burning portion of the mixture, to a point which may be considerably above its auto-ignition temperature. Whether or not it knocks, depends upon two characteristics of the fuel: 1) the auto-ignition temperature; 2) the time lag characteristics of the fuel. If it is kept at a sufficiently high temperature for a sufficient length of time, it will knock. If not, the flame front will pass through it and it will participate in the normal combustion. While all fuels show a decreasing time lag with increasing temperature, the shape of the temperature time-lag curve may vary considerably.

The mechanism of normal combustion is very different from that of auto-ignition. Auto-ignition lag is not necessarily an important factor in the normal process of combustion. Auto-ignition lag should not be confused with the period between the spark and the perceptible pressure rise.

The effect of knock will depend on two factors: 1) the rate of pressure rise during knocking; 2) the magnitude of this pressure rise. The first factor is determined by the reaction rate of the portion of the charge which reacts simultaneously, and the second factor is determined by the magnitude of this portion. Note that, while the rate of pressure rise during knocking is determined by the reaction rate, the rate of pressure rise during normal combustion is largely a function of the flame speed and only secondarily dependent upon the rate of chemical combination in the reaction zone. The rate of pressure rise in the simultaneously reacting portion of the charge determines whether or not appreciable pressure waves will be formed inside the cylinder. Some experimenters clearly state that there are no pressure waves of appreciable magnitude within the cylinder. The presence of sound waves outside the cylinder and of vibrations of the cylinder head itself lead others to believe that it would be strange indeed if there were no pressure waves inside the cylinder. Within the author's knowledge, no satisfactory measurement of pressure waves has been made, but each and every piece of apparatus that has been used in the laboratory at the Massachusetts Institute of Technology has indicated their presence during knocking. This includes many forms of instantaneous cylinder-pressure indicators and some instruments especially designed for the study of knocking. It is obvious that, if pressure is generated with extreme rapidity in one side of the cylinder, the conditions are favorable for setting up a pressure wave. The existence of waves, however, is not important to the main thesis of this article.

There are two factors in the "severity" of knock, namely, the rate and the magnitude of the pressure rise. Any effects due to waves will depend on these factors. We are attempting to measure both of these with a single numerical unit when we use the Midgely bouncing pin, the temperature plug, or the audibility method of determining knock. It is obvious that no one numerical unit can express both these factors and that different methods of measuring knock may give different results, in that one may depend more on the rate of pressure rise while the other depends more on the magnitude of pressure rise. By way of illustration, it has been found in this laboratory that, when running an engine with an advanced spark, the knock noted by ear may be extremely severe, but when the spark is retarded and the compression ratio raised to give the same reading of the Midgely bouncing pin, the audible knock will be considerably reduced, or even scarcely noticeable. It may be that for all practical purposes we may use some such instrument as the Midgely bouncing pin and neglect what it is actually attempting to measure. It is my belief, however, that there is a very real need for a better instrument. In designing such an instrument, it should be borne in mind that our primary interest in the knock rating of fuels for automotive use is the objectionable noise, while for aircraft use, our primary interest is the destructive effect of knock. Therefore, an instrument which is suitable for use in testing automobile fuels, may be of little value for use with aircraft fuels.

If the foregoing theory is correct, it is possible to have two fuels of different auto-ignition temperatures, which will still have similar knocking characteristics under certain conditions. One fuel with a relatively low auto-ignition temperature and a long ignition lag, may burn the same weight of charge simultaneously as a fuel with a much higher auto-ignition temperature but a shorter ignition lag. This will occur only under certain operating conditions. For instance, an increase in speed will cause both fuels to auto-ignite a smaller weight of charge, but the difference will be greater in the case of the fuel with the long lag. Other operating factors will change the relative amounts of auto-igniting charge, but changing other variables may change the time of combustion as well as the temperatures in the cycle, thus rendering it difficult to predict how the relative knocking of two fuels will be affected. If a fuel is knock-rated at some set of conditions, say 212°F. jacket temperature, 600 r.p.m., 70°F. intake air, and then at some other set of conditions, say 212°F. jacket temperature, 1,200 r.p.m., 70°F. intake air, let us define the difference in octane ratings under the two conditions as the "depreciation" of the fuel. From data obtained on six different fuels, including a straight-run gasoline, three gasolines cracked by different processes, a benzol blend, and an ethyl gasoline, it has been observed in this laboratory that raising the speed and increasing the temperature of the charge, either by heating the intake air or by increasing the jacket temperature "depreciates" fuels in proportional amounts, except in the case of the ethyl gasoline, which will be considered later.

Due to the high cost of octane, secondary reference fuels are used in knock-rating. These fuels were chosen because they show no depreciation with either temperature or speed; in other words, they have the same knocking characteristics as octane and heptane. Figure 1 is a graph of the depreciation with increasing jacket temperature against the depreciation with increasing engine speed, the depreciation in this case being expressed in terms of the secondary reference fuels, C-6 and A-2. Since the secondary reference fuels show no depreciation, it is permissible to add an octane scale at the side of the graph. The remarkable thing about this graph is the definite relation between depreciation by two entirely unrelated variables. This tends to confirm our theory that there are two important variables and two only in the characteristics of the fuels studied (with the exception of lead blends) which determine its knocking tendency.

Granting the hypothesis that the ignition temperature and the ignition lag are the two characteristics of the fuel which are important in knocking, the depreciation of a fuel with increasing engine speed can be explained. If a fuel has a high ignition temperature and a short ignition lag compared to an octane-heptane mixture which it matches in knocking at low speed, it is easy to see that its knocking will be less affected by speed changes (changes in the rate of combustion (reference 3)) than the knocking of the reference fuel, and that consequently it will depreciate with the speed. The effect of charge temperature is much more difficult to see , because raising the charge temperature increases the flame speed and changes the available time as well as raising the temperature just before ignition. Raising the temperature of the charge will cause all fuels to knock more readily, but the anti-knock value of fuels which have a long ignition lag will be favored by the greater flame speed. The behavior of a fuel with tetraethyl lead is complicated by the known fact that it is the decomposition products of tetraethyl lead which produce the anti-knock effect. The extent to which these products are present is possibly affected by the temperature of the charge, which may account for the observed fact that the speed depreciation and the temperature depreciations of a leaded fuel do not bear the same relation as with other fuels. (Fig. 2.)

Further evidence that knocking is compression ignition is offered in the report of A. W. Pope, Jr., and J. A. Murdock (reference 7) in the form of a curve of compression ratio for auto-ignition (C.F.R. engine) which is reproduced here. Note the anomolous behavior of fuels with tetraethyl lead. Under the conditions of this test, as in knocking, ignition lag is an important factor. This accounts for the accuracy with which the points fall on the curve.

It is realized that the foregoing conclusions are based on incomplete evidence, and the author would welcome criticism and discussion from others who have experimented in this field.

Massachusetts Institute of Technology,
Cambridge, Mass., February 4, 1933.

REFERENCES

1. Withrow and Boyd: Industrial and Engineering Chemistry, Vol. 23, 1931, p. 539.

2. Schnauffer, Kurt: Das Klopfen von Zündermotoren. D.V.L. Jahrbuch, 1931, p. 375.

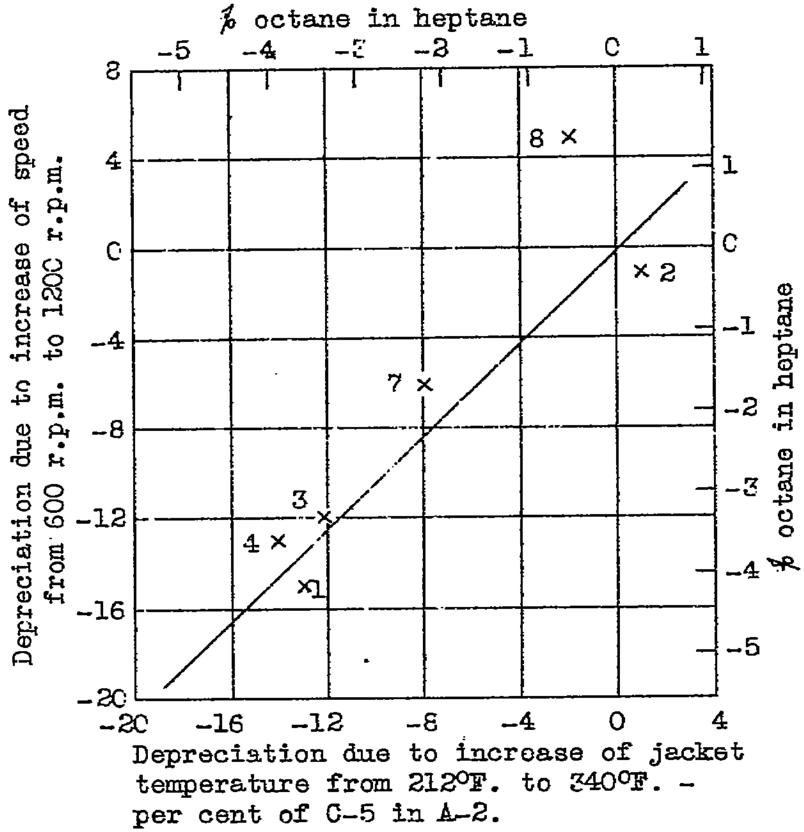
3. Marvin, Charles F., Jr., and Best, Robert D.: Flame Movement and Pressure Development in an Engine Cylinder. T.R. No. 399, N.A.C.A., 1931.

4. Tizard and Pye: Philosophical Magazine, May, 1926.

5. Pye, D. R.: The Internal Combustion Engine. Oxford Press, 1931, p. 25.

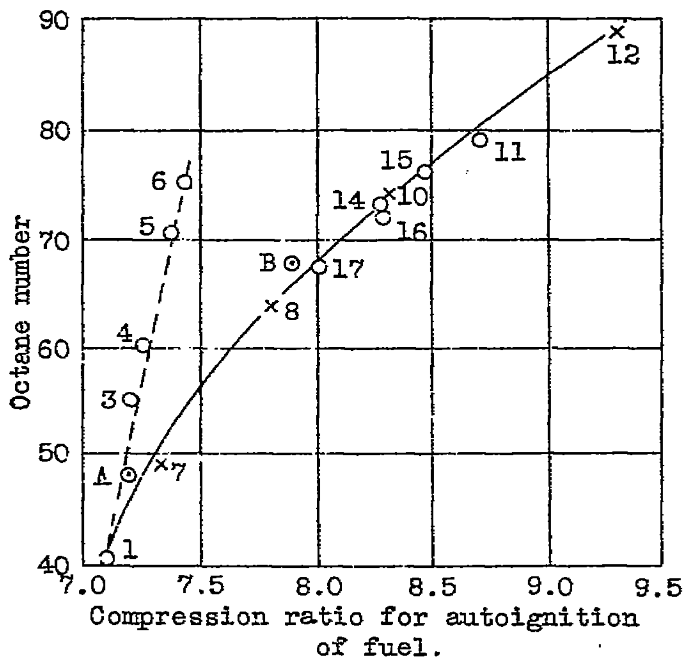
6. Fenning, R. W., and Cotton, F. T.: Experiments or the Ignition of Gases by Sudden Compression. R. & M. No. 1324, British A.R.C., 1929.

7. Pope, A. W., Jr., and Murdock, J. A.: Compression-Ignition Characteristics of Injection-Engine Fuels. S.A.E. Journal, March, 1932, p. 136.



Points 1,4,3 cracked gasolines.
Point 2 reference fuel B-2
Point 7 reference fuel B-2 + benzol.
Point 8 reference fuel B-2 + tetra-
ethyl lead.

Figure 1 Depreciation in knock-rating due to increase in speed against depreciation in knock-rating due to decrease in jacket temperature.



Points 3,4,5 and 6 represent the same gasolines as point 1, with various additions of tetraethyl lead. Points 7,8,10 and 12 refer to the same, blended with benzol. A and B are reference fuels, and other points are for various gasolines.

Figure 2. Compression ratios required for autoignition of gasolines of various octane ratings.